The First Stars: Final Remarks

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How did star formation begin in the universe? Can we make any credible predictions, and can we find any traces of the first stars? We have only recently begun to be able to address these questions in any depth, thanks to a rapidly developing understanding of the history of the universe and to increasingly powerful instruments, and our efforts to answer them have formed the subject of this stimulating first conference on "The First Stars". In these final remarks, I shall try to summarize from a theorist's perspective some of the questions that have been addressed here, and offer some brief comments on what we may have learned so far.

How did the first stars form? In the standard hot-big-bang picture, essentially no heavy elements were produced during the big bang, and the first stars must therefore have formed without any heavy elements. This changes and simplifies the physics of star formation compared with the present situation, since the important physical processes then involve only various forms of hydrogen; the cooling of the first star-forming clouds, for example, is controlled by molecular hydrogen. The thermal behavior of the first collapsing clouds is becoming relatively well understood, thanks to the work of several groups as reported here, and a general conclusion is that the first star-forming clouds must have been hotter than present-day molecular clouds by one or two orders of magnitude in temperature. This higher temperature means that thermal pressure must have been more important for early star formation than it is at the present time, and also that the Jeans mass must have been higher for similar cloud pressures or densities. Even in non-standard cosmologies, the amount of heavy elements that can be produced during the big bang is still very small, and probably too small to change the conclusion that heavy elements played no important role in the formation of the first stars.

When and where did they form? Recent progress in cosmology has narrowed the class of popular models to several variants of the standard CDM model which predict that the first collapsed structures formed at redshifts between about 20 and 50 and had masses between about 10^5 and $10^8\,M_\odot$. The work reported here has mostly focused on a 'typical' case in which the first 3σ density peaks collapsed at a redshift of ~ 30 and formed bound structures with masses of the order of $10^6\,M_\odot$. In this case, the first population III stars are predicted to have formed at a redshift of ~ 30 in small systems whose total masses were of the order of $10^6\,M_\odot$ and whose baryonic masses were of the order of $10^5\,M_\odot$. The formation of metal-free stars need not have occurred only at such high redshifts, however; lower-amplitude primordial density peaks still unenriched in heavy elements could have continued to collapse and form metal-free stars at smaller redshifts, and the formation of metal-free stars could conceivably have continued until much more recent times in the least dense and most slowly evolving 'backwaters' of the universe.

What were their typical masses? In the detailed simulations reported here, the dark matter in the first collapsing structures virializes to form small dark halos, while the baryonic matter settles into flattened configurations in which the Jeans mass is of the order of $10^3\,M_\odot$. This result does not seem to depend very much on the details of the simulations, but only a few cases have been studied so far. Studies of present-day star formation suggest that the Jeans mass may play an important role in determining typical stellar masses, and the simulations reported here also suggest this, showing the formation of a small number of dense collapsing gas clumps whose typical mass is of the order of $10^3\,M_\odot$. A considerable mass range for the clumps is also suggested, extending from less than $10^2\,M_\odot$ to more than $10^4\,M_\odot$. Little tendency is found for these clumps to fragment into smaller objects as the simulations are pushed to higher densities, in agreement with our understanding of present-day star formation which suggests that the outcome of the collapse of Jeans-mass clumps is the formation of at most a small multiple system, so it seems likely that the first stars were indeed typically very massive.

Were any low-mass population III stars formed? Fragmentation to much smaller masses can occur if some of the gas collapses into thin filaments, as indeed happens in some simulations. The fragmentation of such filaments is ultimately limited by the onset of high opacity to the cooling radiation, and in metal-free gas the lower mass limit set by opacity is comparable to the Chandrasekhar mass and somewhat above one solar mass. This is an important result because it means that no metal-free stars should remain visible today; all such stars should by now have evolved. This may explain why we now see no metal-free stars, although it is not yet clear whether we can argue the inverse, namely that the fact that we see no metal-free stars means that the first stars formed must have been exclusively massive. Similar effects may explain why we apparently see fewer than expected extremely metal-poor stars, and it will be interesting to study the effect of a finite but low metallicity on star formation to see whether there is a threshold metallicity above which significant numbers of low-mass stars can form.

What effects did they have? The apparent reionization of the universe at a redshift larger than 5 could in principle have been caused by a small number of massive population III stars formed at high redshifts, but the ionization history of the universe was probably more complex than this, and the effects of the first stars may initially have been rather local and limited by negative feedback effects. One such feedback effect might have been the dissociation of hydrogen molecules by UV radiation before most of the gas became ionized; this might have suppressed further star formation by removing the possibility of cooling by molecular hydrogen. Star formation might have picked up again when larger regions of the universe collapsed and created systems with more internal structure and densities high enough to provide self-shielding from the dissociating UV radiation. Simple predictions of ionization effects are not possible in this more complex situation, but a general expectation illustrated by numerical simulations is that the low-density parts of the universe became ionized first and that the denser regions took longer to become ionized.

How did metal enrichment begin? The first stars must also have produced the first heavy elements. Stars more massive than about $200\,\mathrm{M}_\odot$ are predicted to collapse completely to black holes, and therefore they should not contribute to heavy-element production. But stars with masses between about 100 and $200\,\mathrm{M}_\odot$ are predicted to disrupt entirely due to the pair-production instability, so stars in this mass range are plausible candidates for the first sources of heavy elements. Stars with smaller masses, perhaps between 40 and $100\,\mathrm{M}_\odot$, may again collapse to black holes and not contribute to nucleosynthesis, but still smaller stars with masses between 10 and $40\,\mathrm{M}_\odot$ may produce type II supernovae and provide a second source of heavy elements, if significant numbers of such stars were formed. It is less straightforward to understand how the heavy elements produced by these stars became mixed into the surrounding medium and incorporated into subsequent generations of stars; not until this had happened could the formation of stars of finite metallicity begin. The dispersal and mixing of heavy elements is a complex process, and it was almost certainly not as efficient as has usually been assumed in simple models of the chemical evolution of the universe; chemical enrichment may initially have been quite localized. Supernova-driven winds and galaxy mergers may have contributed to dispersing the heavy elements, but the universe may well have remained chemically very inhomogeneous up to the present time.

Where are the first stars or their products now? If the first stars typically had masses of the order of $10^3\,\mathrm{M}_\odot$, they would mostly have collapsed into black holes with masses of this order. Simulations that keep track of the locations of the first stars or their remnants show that these first condensed objects, which formed in the densest parts of the universe, typically became incorporated through successive mergers in systems of larger and larger size, and typically ended up in the inner parts of present-day large galaxies. If significant numbers of black holes with masses of 10^3 or even $10^4\,\mathrm{M}_\odot$ were present at early times in the inner parts of large galaxies, they might have played a role in the formation of the central supermassive black holes of AGNs. One of the remnants of the early population III stars might have served as a seed for building up a supermassive black hole by accretion, or many of them might have merged into a single much larger black hole because of strong gravitational drag effects in the dense environment of a forming galactic nucleus. Conceivably, most of the first stars or their remnants could have ended up in the central black holes of AGNs!

The heavy elements produced by the first stars may also have ended up mostly in the inner parts of large galaxies. Heavy-element abundances in galaxies are observed to increase towards their centers, and also to increase systematically with galactic mass. Neither of these trends is fully explained by standard models, but both might be explainable if heavy elements produced by the first stars contributed significantly to the observed abundances. The innermost parts of the largest galaxies were the first regions to make stars and heavy elements, and if the first stars formed were predominantly massive, high abundances of heavy elements could have been produced in these regions. The high metallicities of some quasars might also be explainable in this way.

Were they closely related to the oldest observed stars? The hypothetical 10^6-$M_\odot$ systems that formed the first stars probably cannot be identified with any observed systems, and they probably did not form the oldest observed stars because they would have been too short-lived and too weakly bound to retain any gas or heavy elements. The first systems capable of self-enrichment were probably larger systems formed somewhat later by the collapse of larger-scale cosmological structures. These early star-forming systems may have resembled dwarf galaxies, but they probably cannot be identified with observed dwarf galaxies like those in the Local Group since the latter objects inhabit low-density regions and are actually relatively young systems, being dominated in many cases by stars of intermediate age. Thus the observed dwarfs may have been 'stragglers' that formed relatively late in low-density regions of the universe, and not the birthplaces of the first stars. Globular clusters, another once-popular candidate for the sites of the first star formation, are almost certainly not primordial self-enriched objects, since their internal chemical homogeneity cannot be explained without very contrived assumptions unless they were formed in larger pre-existing systems that provided an environment for chemical enrichment and mixing to take place.

How did the first observed stars form? A notable property of the dwarf galaxies in the Local Group is that they appear to have a minimum mass of about 2×10^7 $M_\odot$, regardless of how faint or metal-poor they may be. This may be the minimum mass that a galaxy needs to retain gas and heavy elements, and thus to allow continuing star formation and self-enrichment to occur. In fact, this mass is about the minimum required for a galaxy to bind ionized gas at a temperature of 10^4 K; retaining ionized gas is necessary to sustain star formation and chemical enrichment because massive stars quickly ionize the surrounding medium as soon as they form, and the interstellar gas in a typical galaxy goes through many cycles of ionization and recombination before being incorporated into stars. This cycling process also plays an important role in chemical enrichment, since the heavy elements produced by supernovae are probably dispersed and mixed mainly in an ionized medium.

Many complex astrophysical processes must therefore have occurred prior to the formation of the first observed stars, and star-forming systems at least as massive as present-day dwarf galaxies may have been required. These early star-forming systems might also have been the birthplaces of the first globular clusters. However, nearly all of them would by now have been destroyed by being merged into larger galaxies, and the globular clusters may be their only surviving remnants.

What can we learn from element abundances? Much attention has been given at this meeting to chemical abundances in old stars, but this subject has many intricacies, and their implications for our understanding of early star formation and galaxy evolution are not yet very clear. Some of the abundance patterns in very metal-poor stars seem compatible with element synthesis in predominantly massive stars, and this might be consistent with enrichment by an initial metal-free population consisting mostly of massive stars; however, the origin of the heavy elements in these very metal-poor stars cannot yet be identified with certainty.

We are just beginning, in any case, to appreciate the true complexity of the chemical enrichment of galaxies and the universe. Clearly it is completely misleading to imagine that heavy-element abundances are correlated in any simple way with time and can be used as a clock; instead, it is clear that the densest parts of the universe and of individual galaxies evolved more rapidly and became chemically enriched much earlier than the less dense regions. The universe must therefore have evolved in a chemically highly inhomogeneous way; "old" and "metal-poor" are not synonymous. Even in the solar neighborhood in our own Galaxy, chemical enrichment must have been a very non-uniform process, since the metallicities of nearby stars and clusters show a large scatter and only a weak trend, if any, with age. All of the standard models of chemical evolution fail badly to account for these observations, and we need to go back to the drawing board with these models because our present understanding of this subject is still primitive.

So, much has been learned, but much remains to be done. It is an encouraging sign of progress that we have even been able to make a start in answering some of the questions mentioned above. Let us look forward to many more fruitful meetings as we continue the quest to understand the first stars.